

Navigation Results from Desert Field Tests of the Rocky 7 Mars Rover Prototype

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Abstract

Upcoming missions to the surface of Mars will use mobile robots to traverse long distances from the landing site. To prepare enabling technologies for these missions, the prototype rover, Rocky 7, has been tested in desert field trials conducted with a team of planetary scientists. While several new capabilities have been demonstrated, foremost among these was sun-sensor based traversal of natural terrain totaling a distance of one kilometer. This paper describes the new technologies incorporated into Rocky 7, and details the navigation results obtained in the field tests. Accurate position estimation is shown as a significant improvement over previous mission results, and methods for further improvement are discussed.

1 Introduction

In 1997, NASA revisited the planet Mars for the first time in twenty years. The *Pathfinder*¹ lander contained the mobile robot, *Sojourner*, a 12 kg six-wheeled mobile robot which ventured out from the lander, taking pictures and positioning a science instrument against designated soil and rocks. Based on previous rover prototypes [8], *Sojourner* was designed to demonstrate the viability of mobile robot exploration of Mars.

Current plans are to build upon this successful test of a planetary rover with longer range traversals across Mars beginning in 2003. Therefore, we have been investigating next generation prototype rovers with more manipulation, mobility, autonomy, and general functionality [15].

This paper describes our next generation prototype rover, *Rocky 7*, and its successful desert field trials of the long range mission scenario². Among the important new capabilities demonstrated are: accurate sun sensor based navigation over long distances, operator control using rover-centric imagery, traversal contextualization from panoramic mosaics and nested descent imagery, and remote autonomous scientific exploration of an extended geologic area.

¹<http://mpfwww.jpl.nasa.gov/>

²<http://robotics.jpl.nasa.gov/tasks/lrsr/>

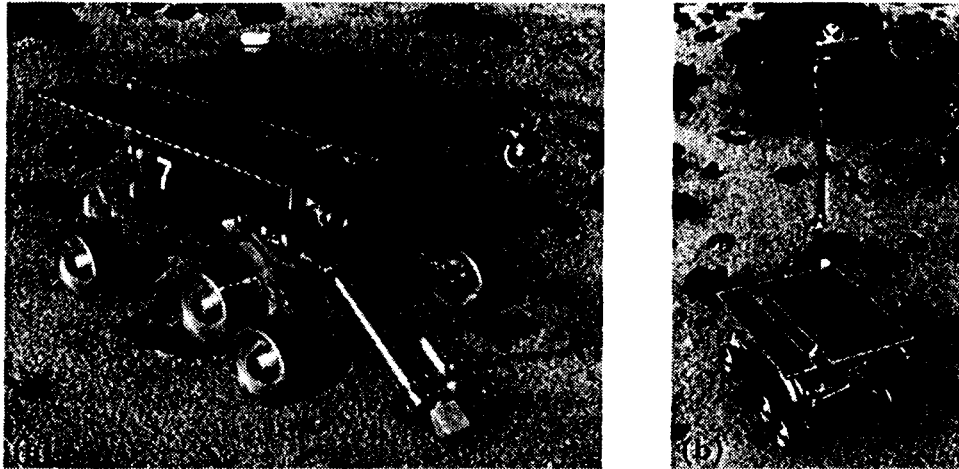


Figure 1: The Rocky 7 rover with (a) arm deployed, or (b) mast up.

This paper is organized as follows: Section 2 describes many of the features of our test vehicle, Rocky 7, followed by a description of its navigation command and control strategies in Section 3. Section 4 provides an overview of the desert field test objectives and implementation. Experimental results are presented and analyzed in Section 5, and the indicated areas and methods for improved performance are discussed in Section 6.

2 Rocky 7 Overview

Figure 1 shows the Rocky 7 next-generation Mars rover research prototype. Whereas Sojourner employed technology demonstrated in previous prototypes (e.g. Rocky 3 and 4), Rocky 7 was designed to advance rover technology for future missions, such as the upcoming Mars Surveyor Rover Mission³. Among these rover technologies are: reduced actuator mobility, appendages and algorithms for sampling and periscopic viewing, improved actuation and sensing, computationally intensive sensor processing, and a contemporary computing environment [16, 17, 18]. Also required for terrestrial tests were well designed power and thermal systems. Each of these will be discussed below.

2.1 Mobility and Manipulation

Rocky 7 is slightly larger and heavier than Sojourner, being $60 \times 40 \times 35 \text{ cm}^3$ and 15.5 kg. Like Sojourner, Rocky 7 employs a *rocker-bogie* six wheel configuration [5]. However, unlike its predecessors with four corner steering, Rocky 7 only has steering capability on two corners, driving like a car or fork-lift. Also, the wheels on each rocker have been moved close together. While not greatly reducing its step climbing capability (greater than 1.2 wheel diameters), this configuration creates the possibility of mechanically or electrically controlling these two wheels together. In this way, the number of degrees-of-freedom (DOFs) for mobility has been reduced from ten to six. The cost of this change is an inability to

³<http://mars.jpl.nasa.gov/>

turn in place about the center of the vehicle, as with four corner steering. Instead, the nominal rotation axis for Rocky 7 is located mid-way between the double wheel pairs. (Tank steering can be used to approximate turn in place operations, but the extensive wheel slippage corrupts odometer information, and causes the vehicle to sink into soft soils like those expected on Mars.)

The four DOFs saved with the new wheel configuration have been used for a manipulator that can sample soil or rocks, and point or bury science instruments, as shown in Figure 1(a). This small arm has a two DOF shoulder that can store it across the front of the chassis, reach down to 10 cm below the surface, or move in a conical fashion in front of the vehicle to point an integrated spectrometer. The end-effector of the arm has two independently drivable scoops, which can rotate continuously. In this way, they can be positioned as a clamshell to scoop and store soil samples, or back to back to form a parallel jaw gripper with side tongs allowing rock and cylindrical instrument grasping. Also, when rotated together through 360°, they deploy a white target stored in the fork of the end effector. This target is used for calibrating a built-in spectrometer [17].

A second, longer, 3 DOF manipulator deploys through a slot in the solar panel, and is referred to as “the mast”, as shown in Figure 1(b). It carries an integrated sensor package which has stereo cameras with counter rotating filter wheels, and an interchangeable instrument canister. The primary function of the mast is to extend to a height of 1.4 meters from ground level and rotate 360 degrees to provide panoramic imagery. It can also look down at the surrounding terrain or the rover itself, enabling visual self-inspection from all directions. This dexterity also enables the positioning of the instrument canister on nearby rocks and soil. Typically the canister is outfitted with a gimbaled close-focus camera, but mast payload specifications (0.5 kg) are designed to allow the replacement of the close-up imager with another science instrument, such as the Mössbauer spectrometer used in the desert tests⁴. Finally, when stowed the arm does not cast a shadow on the solar panel, block the navigation cameras, or impede the motion of the rocker-bogeys.

2.2 Actuation and Sensing

Rocky 7’s manipulators and steering wheels use a specially developed modular joint design [18]. Two features of this joint that are of particular value to robotics applications are its hollow axis and backdriveability. The former is valuable since robots typically employ serial chains of actuators, and the hollow axis allows wiring to pass through each joint without service loops. It has also proven useful on Rocky 7 for an optical pathway for the spectrometer integrated into the shorter manipulator. The latter is valuable since back-driveable joints accommodate reaction forces during contact operations, enabling better sensing and control. Also, from a practical standpoint, during development joints may be manually moved when unpowered.

To control the motors in all actuators of the rover, we have developed a customized independent joint control system. While similar capability can be obtained from off-the-shelf hardware, limitations in mass, power, and volume, required the development of custom electronics. Each motor is servoed with a proportional-integral-derivative (PID) control loop that relies on the input of quadrature encoder measurements of joint position, and creates a

⁴<http://astrosun.tn.cornell.edu/athena/mossbauer.html>

pulse-width-modulated (PWM) output for motor current. This type of motor control allows accurate positioning of the appendages, and variable speed trajectory profiles for slipless wheel acceleration. Motor current is also measured for use in certain applications, such as contact detection while digging.

Beyond the encoders and current sensing, Rocky 7 has a full suite of navigation sensors. The configuration of the rocker-bogey suspension is measured with potentiometers, and the tilt of the chassis is obtained with three accelerometers. A quartz rate sensor can measure the rate of rotation of the vehicle about its vertical axis, but this measurement must be integrated to provide heading, making it subject to drift as noise is integrated with the rate signal. The amount of drift is proportional to the total time of integration, and therefore the distance traveled divided by the speed. Faster speeds can reduce the error, but they may also increase vehicle vibration on rough terrain, another source of noise and drift. Optimal speeds are not known at this time. For all of these reasons, absolute heading sensors are a better solution.

On Earth, the magnetic compass is the most common absolute heading device. However, use of a compass is not legitimate for our tests since Mars has a negligible magnetic field. Therefore, to provide a reliable measurement of the vehicle heading we have employed a wide field of view sun sensor. Used in conjunction with the accelerometer readings and an on-board clock, it enables absolute vehicle heading to be calculated. While a camera could be used as a sun sensor, the analog position-sensing-device (PSD) based sensor employed on Rocky 7 is attractive for its fast rate of update and minimal computational overhead [12]. This simplicity and speed come at the cost of increased complexity of calibration, and slight miscalibration did lead to test errors discussed later in Section 5.1. (Subsequent recalibration has been performed, and the sensor is being used in on-going improvements in rover position estimation filters, which rely on the the fast update rate provided by its analog design.)

Although not employed for sun sensing, black and white CCD cameras are used extensively on Rocky 7, for hazard avoidance, navigation telemetry, and science data. Images from pairs of these cameras are captured simultaneously as stereo pairs. Mast imagery is typically returned to the rover operators as panoramic mosaics for use in specified rover traversals. Body mounted hazard avoidance imagery are typically processed on-board to provide depth maps of the environment, and then automatically analyzed for abrupt changes in height or high-centering hazards [10, 17]. Impassable regions are specified to the navigation algorithm through a fuzzy classification of the region position: left, right, or center. The central region is defined as the width of the vehicle extending out to 50 cm. The left and right regions are from either side of the central region to the edge of the field of view. Navigation based on this classification is reviewed in Section 3.

2.3 Computing

To support computationally intensive processes such as stereo image processing, and to provide a contemporary software development environment, Rocky 7 has a 32-bit computer running a commercial hard-real-time operating system (Wind River Systems' *VxWorks*TM). Rocky 7's software architecture is based on the framework provided by Real Time Innovation's *ControlShell*TM [13]. *Control Shell* facilitates the creation of C++ software modules

which are connected into asynchronous finite state machines, and synchronous data-flow control loops. In Rocky 7, asynchronous activities are initiated by a queue of operator commands. On-board the rover, these commands cause state transitions in one of several state machines for navigation, vision, and manipulation. State machine transitions are often used to begin the execution of synchronous processes which perform monitoring and control of the Rover's subsystems.

2.4 Power and Thermal

Power and thermal issues for Rocky 7 are unique to its application as an Earth research test vehicle. Power consumption has been kept in check, but not at the cost incurred on typical space missions, where custom design is the rule. Rocky 7's commercial off-the-shelf (COTS) electronics were selected to provide needed functionality while minimizing power consumption, temperature tolerance, mass, and volume. The resulting system consumes approximate 50W while driving, and is powered by rechargeable NiCad batteries and a quarter square meter solar panel. During typical activities for the rover, batteries must be replaced every 1.5 hours.

Thermal concerns on Earth are governed by the need to keep components cool, whereas on Mars they must be kept warm. To remove heat from the chassis containing the electronics, a bank of fans forces air down under the solar panel. All electronic components in the vehicle are rated to at least 60 degrees Celcius. During the desert field tests described in this report, internal rover temperatures were held within their limits even as ambient air temperature reached 45 degrees Celcius.

3 Rocky 7 Navigation

After the completion of Rocky 7's construction and baseline programming, a series of increasingly lengthy demonstrations were conducted in the JPL MarsYard and the Mojave desert. Contained, herein, are the results of the last of these tests, a simulated mission performed at Lavic Lake lava flow and dry lake-bed on the Twenty Nine Palms Marine Corps Base [2]. During this simulation, Rocky 7 traversed more than one kilometer across four distinct terrains, while commanded remotely by a team of scientists and engineers.

The strategy for a simulated exploration of Mars, as with a real mission, requires the rover to simply go where commanded, within the limits allowed by the on-board safety system [19]. This ability depends on reliable techniques for operator interfacing, mobility, hazard detection, piloting, and position estimation of the rover.

Rocky 7's operator interface is the *Web Interface for Telescience (WITS)*[4]. Through it, an operator is provided with panoramic stereo images taken from Rocky 7's deployable mast, or with aerial images obtained during an emulation of the lander descent (obtained by helicopter). From this imagery, samples of which are shown in Figures 2 and 3, waypoints and science targets are selected and incorporated in a sequential list sent to the rover.

The rover interprets each waypoint as a goal to which it must navigate while avoiding obstacles. Stereo images of the terrain are processed on-board the rover, and some terrain features are interpreted as obstacles [10]. Based on the location of obstacles and the goal

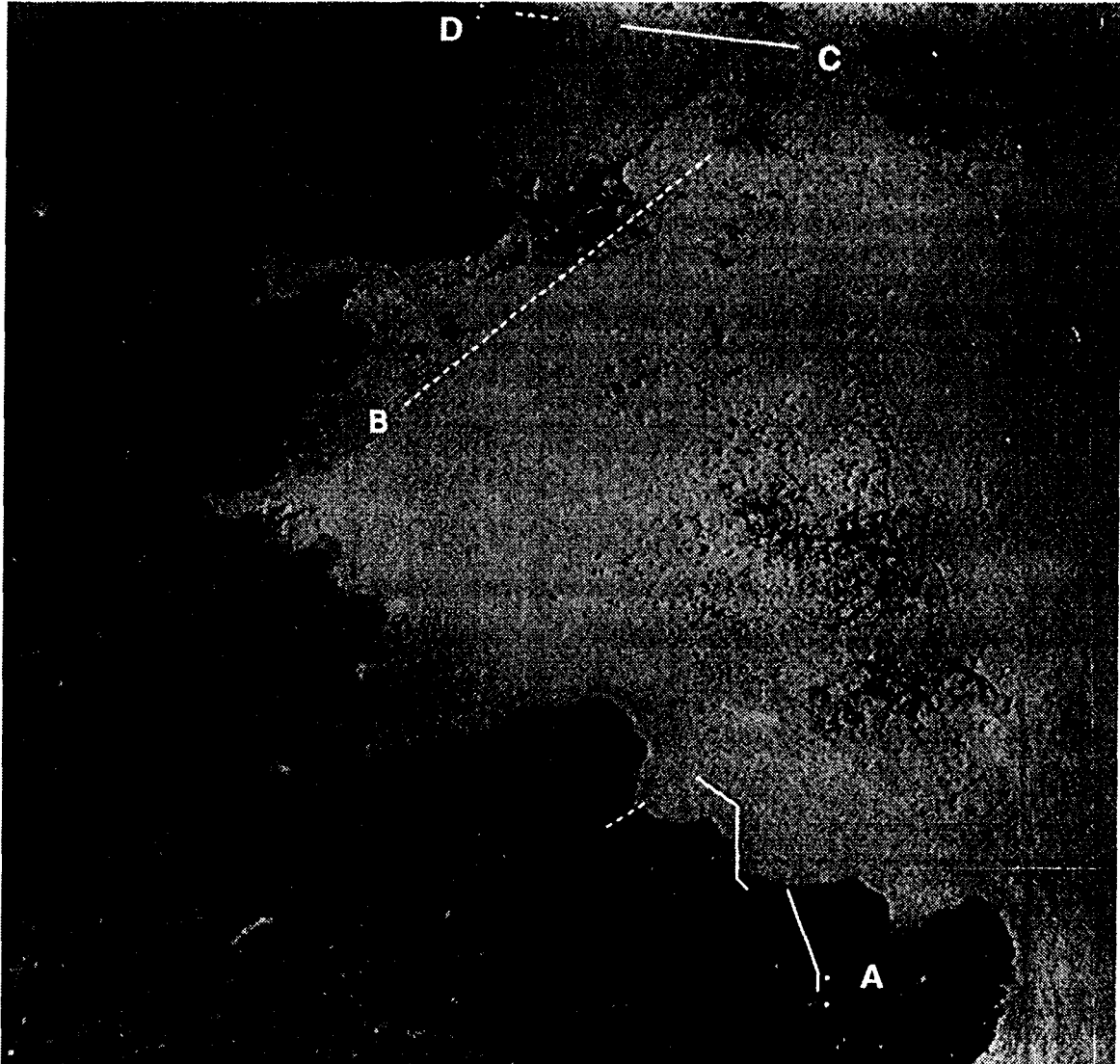


Figure 2: Imagery of Lavic Lake site at 862 m above ground level, taken by helicopter during an emulated lander descent. Letters indicate the location of pre-positioned ground targets. Solid lines indicated the rover traverses discussed in detail. Dashed lines indicate other rover traverses. The direct distance from A to D is approximately 1 km.



Figure 3: Panoramic mosaic taken by the mast cameras of Rocky 7 from the beginning of the traverse from point A in Figure 2. The center of the mosaic is facing north. The large white patch, visible in both views, is a ground target used for guiding the aerial imaging.

with respect to the rover, very simple reactive rules are used to decide its piece-wise motion [15, 8, 6]. That is, the rover either turns in place by one half radian, or moves forward in one quarter meter path segments that are straight or in an arc toward the goal. Then the entire procedure is repeated.

The performance of this entire sequence of activities depends heavily on the accuracy of the position estimate of the rover — globally, locally, and incrementally. Position estimation of the rover is comprised of down-track and cross-track estimation of position as the rover traverses. First order estimates of the down-track position are obtained directly from wheel odometry. But the accuracy of the position estimate is largely dependent on knowledge of heading, because small heading errors can develop into large cross-track position errors during extended traversals. As described in Section 2.2, sun sensing has been employed on Rocky 7 to provide a very useful heading estimate [14].

4 Field Test Objectives and Implementation

The selected site for the field tests was Lavic Lake, a dry lake-bed bordered by a lava flow and geologic fault line. Figure 2 is an aerial view of the test site on the southwestern edge of the lake-bed. This location was chosen specifically for these tests by Ray Arvidson, Chair of Planetary Sciences at Washington University, who led the science team efforts for this demonstration in preparation for his role as Science Operations Lead in the upcoming Mars Surveyor 2003 Rover Mission.

Located on the Twenty-Nine Palms Marine Corps base in the Mojave desert, Lavic Lake was also logistically attractive. First, it is only a three hour drive from JPL, minimizing transportation difficulties. Second, the use of off-road vehicles (including the rover itself) and a radioactive source for the Mössbauer spectrometer was permitted by the Marines. Such permission was not readily available from for the National Park Service or Bureau of Land Management, which have jurisdiction over most desert lands in California. Third, Marine bombing practice has left many portions of Lavic Lake pock-marked with craters, providing a nice Mars analog terrain.

For the engineering team, these tests were designed to provided a demonstration of the system performing long-distance traversals and remote science operations without the aid of a lander. For the science team, such a demonstration would give a preview of rover capabilities and limitations to be expected for upcoming missions. In both cases, it was assumed there would be some validation and some recalibration of expectations and

understanding.

In preparation for the tests, four geologically distinct science sites were chosen within the Lavic Lake area: a lava flow with desert pavement, undisturbed playa, cratered playa, and an alluvial fan. Each of these sites were imaged by helicopter in a nested sequence that emulated planned lander descent images for upcoming missions. Figure 2 shows one image from these sequences which captures all four regions.

The operations center for the tests was located in a trailer parked close to point B. In addition to the emulated descent imagery, the rover operator and scientists made all mission decisions based on information sent back from Rocky 7 in the form of images and other telemetry. A complete log of this information is available over the Internet ⁵.

In addition to the telemetry used for mission planning, two other forms of data were collected. First, a complete log of the rover's on-board command sequencing was captured, as well as rover position estimates at each navigation step. Second, approximately every three meters of traverse the rover position was marked and the time noted. The marked locations were later measured with surveying equipment. The results of these measurements are presented in the next section.

5 Experimental Results

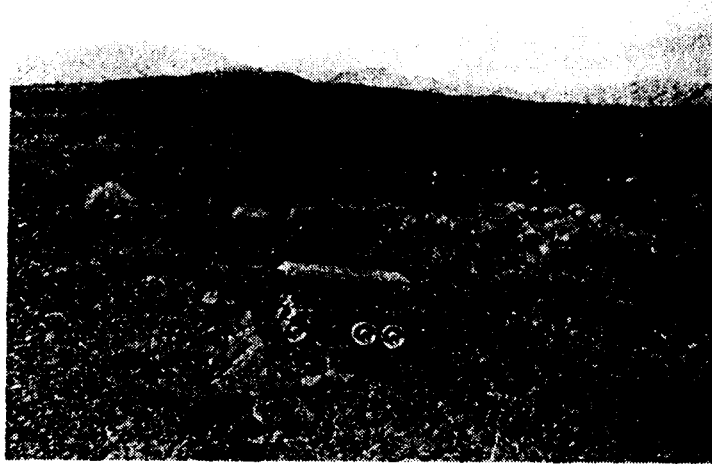
This section presents the rover traverse results during the three segments shown by solid lines in Figure 2. The first segment is closest to the bottom of the aerial view and point A, and is referred to as the 'Sunshine Flow Traverse'. The second segment is just north of this and is referred to as the 'Flow Margin Traverse'. The third segment is between points C and D, and is referred to as the 'Cratered Playa Traverse'. Figures 4 show Rocky 7 and the terrain from ground level during each of these segments.

Figures 5 show plan views of measured positions of the rover during the three traverses. All coordinates are in a frame with east as positive x , north as positive y , and the origin located at the base-station near point B in Figure 2. The dark line in each plot is the on-board estimate of the rover position. The label 'SPICE' is an acronym of the database in which all of the telemetry was stored (*Spacecraft, Planet, and Instrument Configuration matrix and Events* [1]). The squares on each plot are the position of the rover measured by the Ground Truth Station surveying equipment. The accuracy of these measurement is approximately 20 cm, well below the resolution of the plots. Also shown by solid diamonds are the commanded goal positions, which are generically called waypoints (whether they are intermediate or terminal goal points).

Note that the on-board rover position estimate will typically move directly to a waypoint since the rover always 'thinks' it is headed the right way. In those cases where the rover does not reach a waypoint, there has been an error condition which prompted communication with base station, resulting in a new waypoint being provided. Error conditions during the field test had several sources, and could be as simple as inadvertent loss of power due to battery depletion. Also problematic were data drop-outs due to lost radio communication during the traverse. These are indicated by missing portions of the dark lines on the plots.

Figures 6 present the same position data as in Figures 5, but plotted explicitly against

⁵<http://wundow.wustl.edu/rocky7/>



(a) Sunshine Flow: roughest terrain, near beginning of first traverse and A, looking west.



(b) Flow Margin: flow edge at beginning of second traverse, looking north.



(c) Cratered Playa: in shallow crater along third traverse, near C looking northwest.

Figure 4: Views from ground level of traverse terrain for three segments.

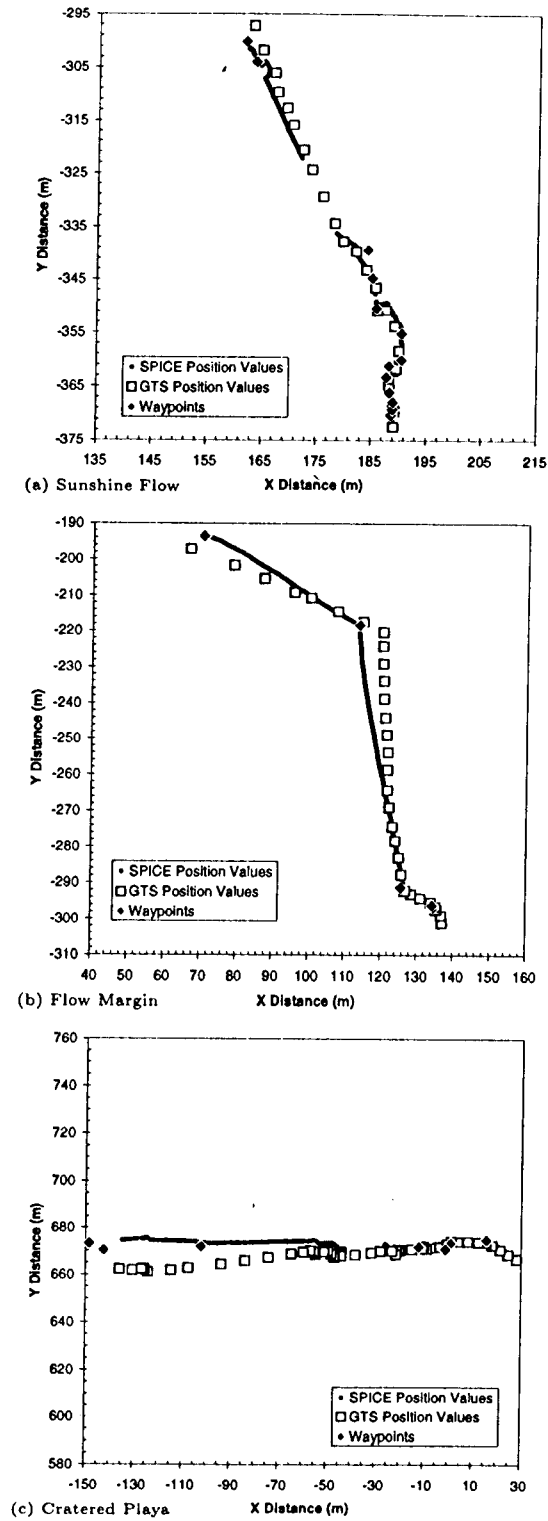


Figure 5: Plan view of three rover traverses, showing estimated, measured and waypoint positions.

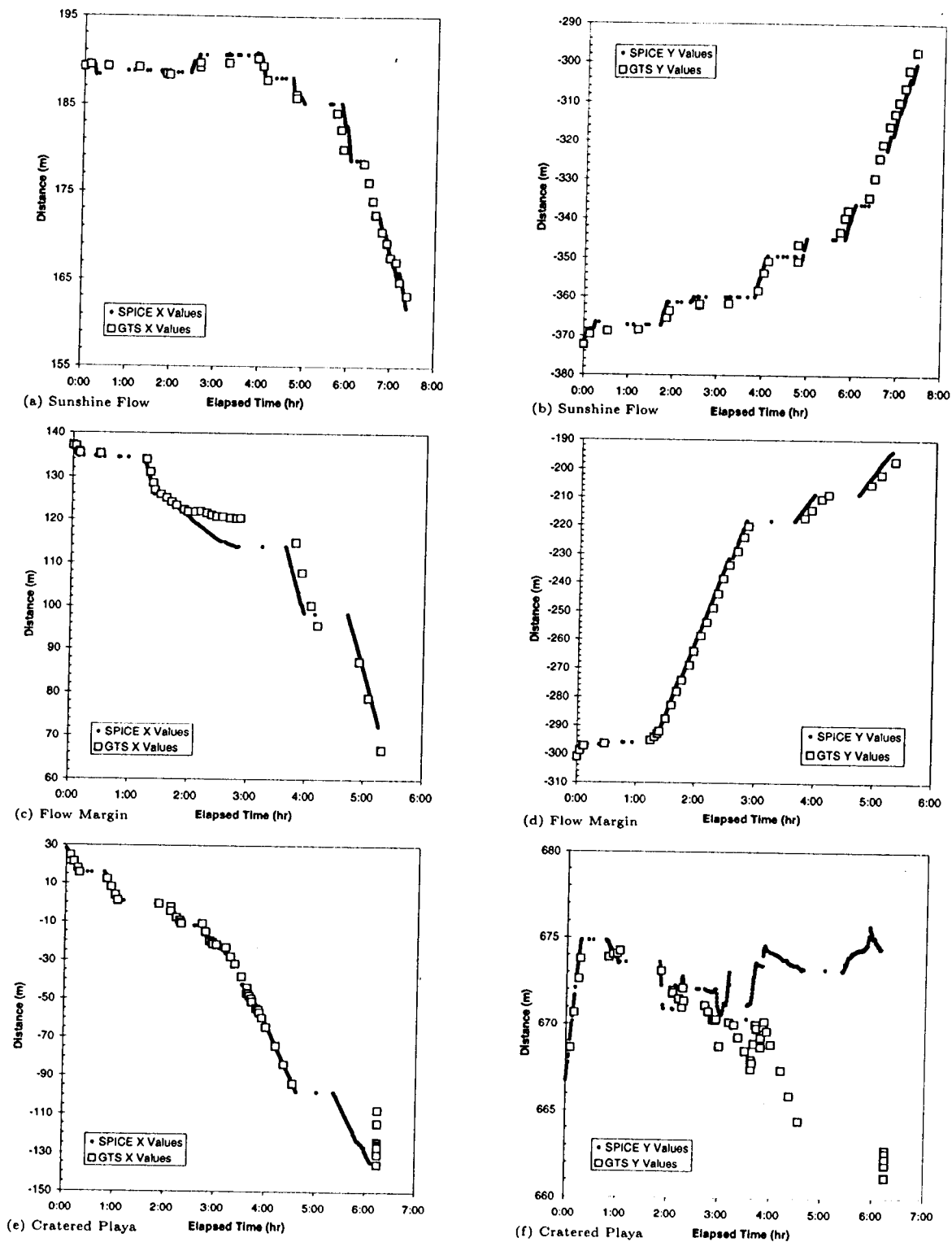


Figure 6: X and Y values over time for the three traverses.

time from the beginning of the traverse. Time passage due to temporal breaks at meals or end-of-day have been ignored, but other time passage when the rover was not moving has been included. Typically the latter was during periods when panoramic images were being taken by the rover, or commands were being generated at the base station. These periods appear as flat portions of the plots and often correspond directly to the positions of the waypoints in Figures 5. A typical cycle of operation involved the rover reaching a commanded position tens of meters away, taking a panorama, and then receiving a new goal based on the new imagery. In a real mission on Mars, each of these cycles would require at least one day, due to limited communication opportunities with the spacecraft.

5.1 Position Error

As described earlier, position error of the rover is comprised of down-track and cross-track error. Figures 7 show the absolute and relative position errors, as well as their down-track and cross-track components. Because of the turn in the middle of the Flow Margin traverse, there is a discontinuity in the component values in Figures 7(c) and (d). From these plots it is apparent that the error grows linearly with distance traveled, and therefore levels out at a constant percentage of the distance traveled. This percentage is slightly different for the three traverses, and is likely the result of different ground traction or errors in heading estimation, as described below. To further distill this data, the absolute position errors from all traverses have been replotted in Figure 8. *A least-squares fit of the points indicates an average relative error of 6%.*

5.2 Heading Error

5.2.1 Obstacle Free Analysis

If the rover is considered to be simply trying to stay in a straight line, the measured position error may be used to determine the heading error. For the sun sensor, a simple sensor model assumes an accurate heading angle plus noise:

$$\theta = \theta_0 + n_\theta \quad (1)$$

For simplicity, we can let $\theta_0 = 0$. Therefore, if the rover speed is v , its (x, y) position will be:

$$x = \int_0^t v \cos n_\theta d\tau \quad y = \int_0^t v \sin n_\theta d\tau \quad (2)$$

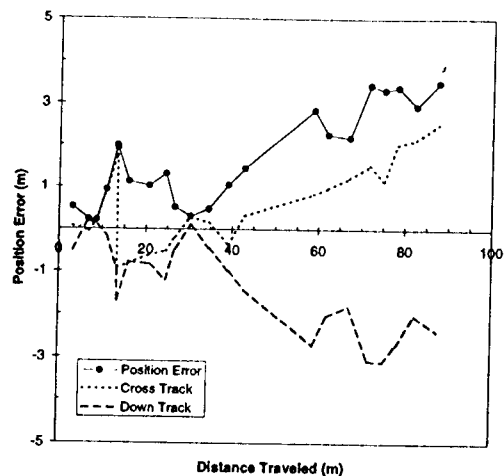
$$x = vt \cos n_\theta \quad y = vt \sin n_\theta \quad (3)$$

In the absence of noise the rover would drive straight. With $n_\theta = 0$, $x = vt = d$, and the position error is:

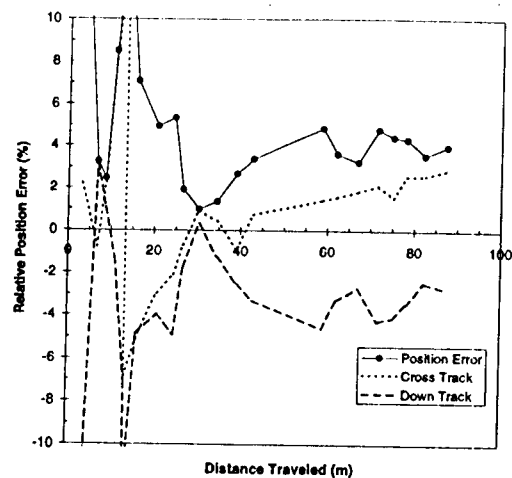
$$e = \sqrt{(vt \cos n_\theta - vt)^2 + (vt \sin n_\theta)^2} \quad (4)$$

$$= 2d \sin \frac{n_\theta}{2} \quad (5)$$

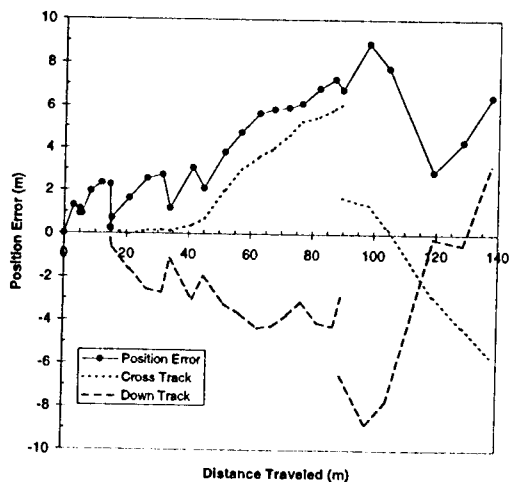
$$\approx n_\theta d \quad (6)$$



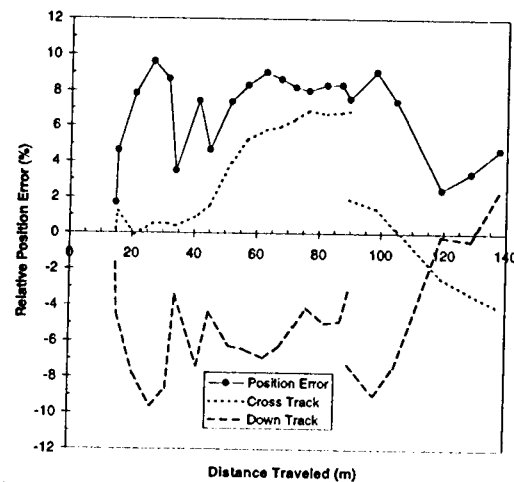
(a) Sunshine Flow



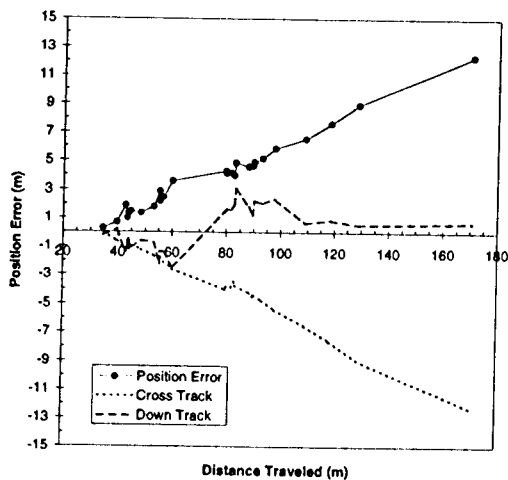
(b) Sunshine Flow



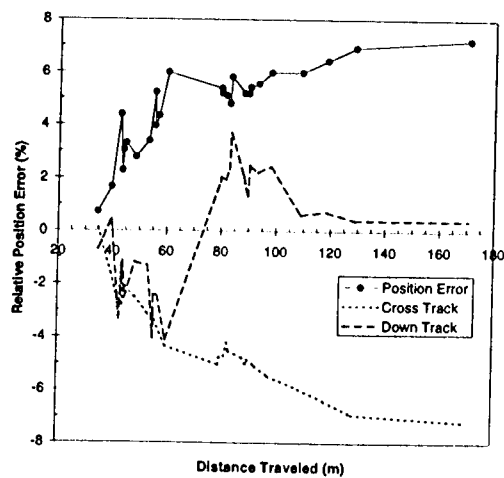
(c) Flow Margin



(d) Flow Margin



(e) Cratered Playa



(f) Cratered Playa

Figure 7: Absolute and relative error for rover position during three field test traversals.

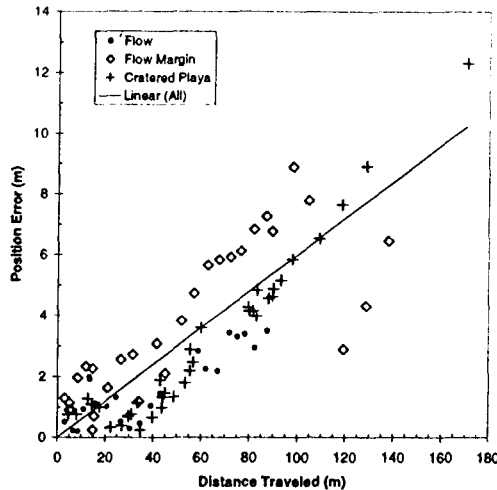


Figure 8: Plot of all absolute position errors versus respective distance traveled for all field test traversals. The least square fit indicates an expected relative error of 6%.

where the approximation is true for small values of n_θ . It is important to note this result shows that with an absolute heading device like the sun sensor, the relative position error is a constant. From the previous section, $e/d = n_\theta = 0.06$ or 3.4° .

5.2.2 Individual Traversal Results

For the experimental traversals performed, two issues complicated the situation beyond simply staying in a straight line. First, terrain considerations required that traversals be composed of intermediate waypoints, which sometimes deviated from exactly straight lines. Second, the rover was actively performing hazard avoidance during the traverses, which added to position error and forced time to be spent at headings other than those to the goal.

For these reasons, it is illustrative to look in detail at the heading of the rover during the individual traversals. Figures 9 show the heading measurements and their distributions for the three traverses. Note that the externally measured heading values, indicated by squares, are very sporadic. This was due to the limited opportunities to measure the orientation of the rover, since it was moving and care was needed to not enter the field of view of the sun sensor or hazard detection cameras.

The heading values represented in the figures may be quantified by looking at the statistics of the measurements, shown in Table 1. Greater deviation in the heading is due to more frequent turning of the rover to avoid obstacles or reach intermediate waypoints. This action is typically marked by large changes, as seen in Figure 9(a). and is consistent with the rough terrain and numerous waypoints of this traverse. Smaller fluctuations in the heading, as shown in Figure 9(b), are often due to other sources such as sun sensor noise, accelerometer noise, or sun sensor calibration error [14].

Experimentation subsequent to these desert field trials has indicated that the sun sensor

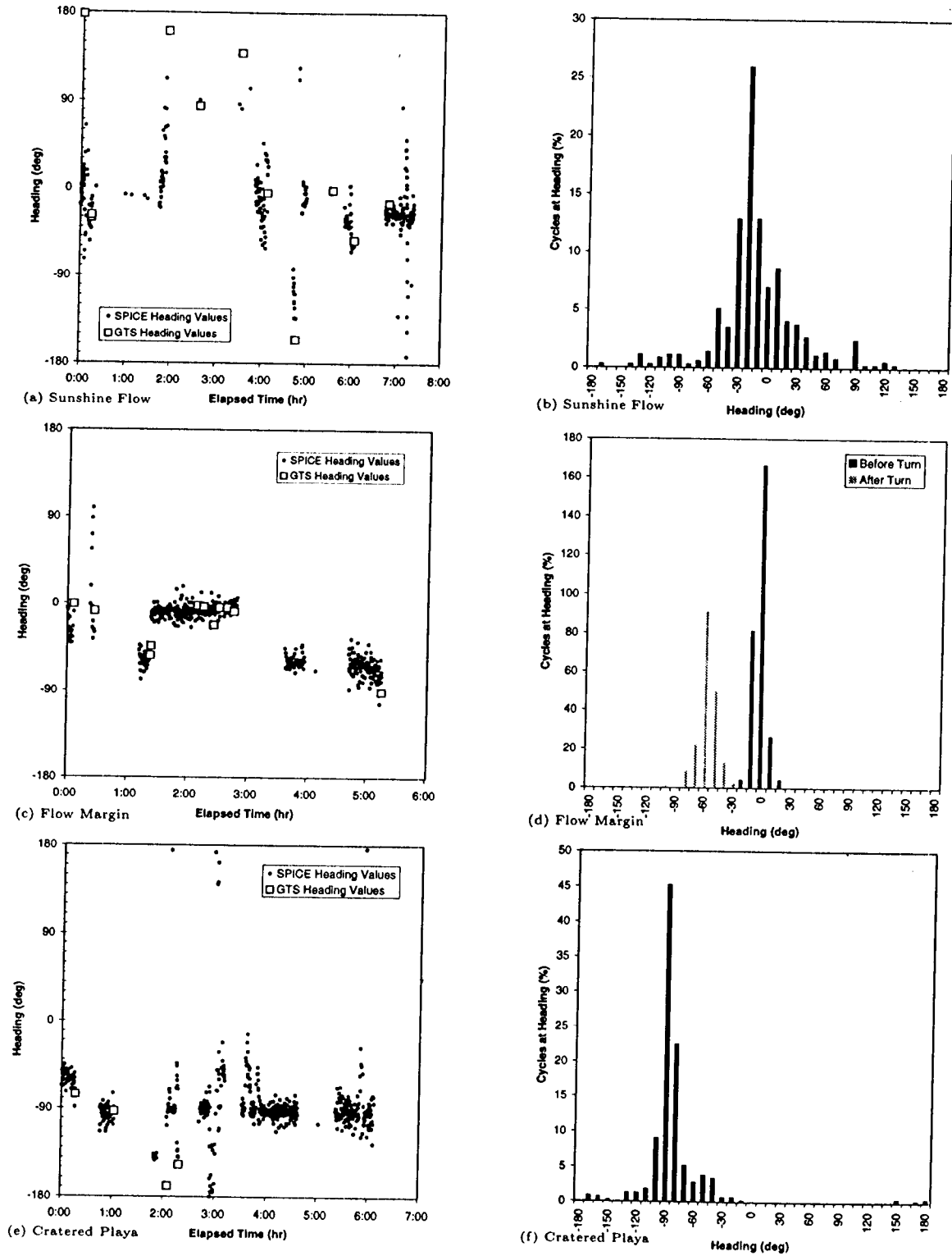


Figure 9: Measured heading and distributions during three field test traversals.

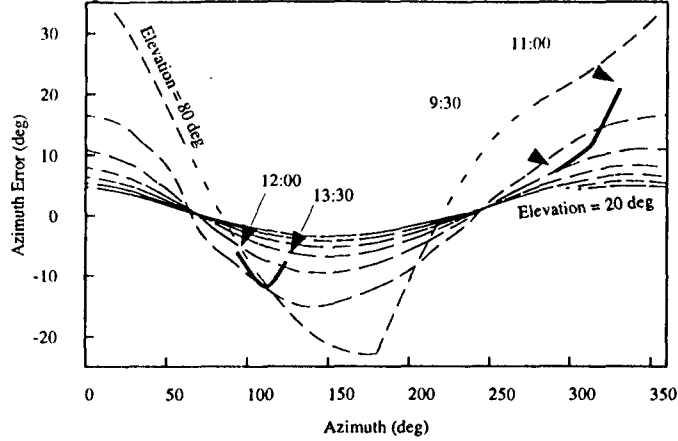


Figure 10: Plot of sun sensor azimuth error versus azimuth with different values of elevation shown by contours. This error is due to slight miscalibration of the sun sensor, but can lead to significant errors. See text for details.

was slightly out of calibration during these traverses. This miscalibration added an orientation and time dependent bias to the heading of the vehicle, and can account for much of the heading bias error which led directly to cross-track error. Figure 10 shows the miscalibrated sun sensor operation range during the traverse shown in Figure 5(b). During the morning (9:30 - 11:00) the operational area of the sun sensor, due to sun position and rover orientation, caused an error opposite in sign to that of the afternoon (12:00 - 1:30). Therefore, in the morning, before the turn, the rover drifted to the right — and in the afternoon, after the turn, drifted to the left. Recalibration of the sensor after the field tests removed this problem.

5.3 Performance Comparison

Even with the calibration error of the sun sensor, the field tests demonstrated an intrinsic performance improvement when compared to other techniques such as odometry and gyro measurements.

5.3.1 Odometry

Odometry based position and heading estimates of the field test traverses may be obtained by post-processing the telemetry data. Figures 11 show the results of using a simple in-

Traverse	Samples	Std Dev	Mean
Sunshine Flow	374	39.5°	-16.7°
Margin Before Turn	281	6.1°	-7.4°
Margin After Turn	188	9.4°	-63.0°
Cratered Playa	500	31.6°	-87.2°

Table 1: Statistical description of heading measurements during traversals.

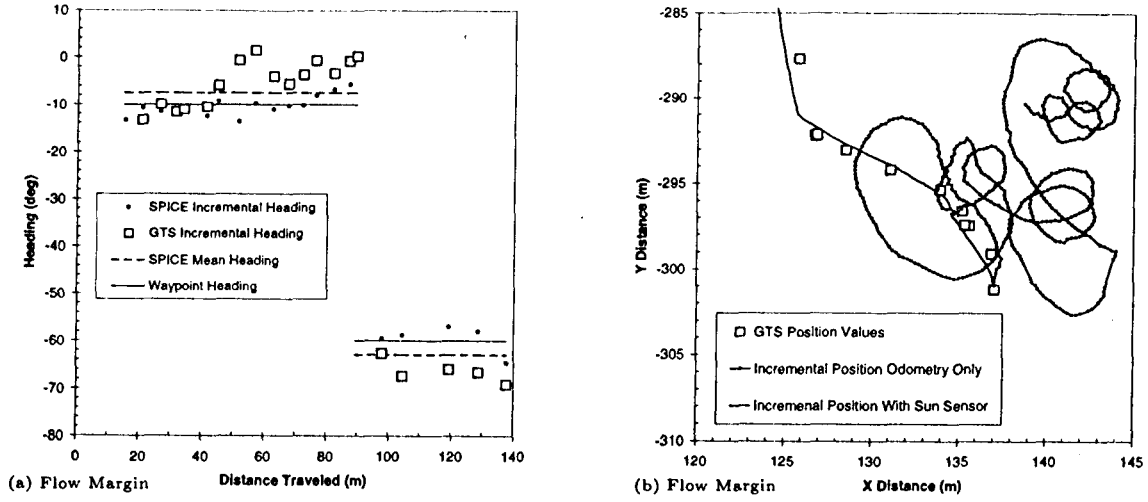


Figure 11: Incremental heading values comparison and position estimate propagation.

cremental estimation from the data of the traverse in Figure 5(b). Figure 11(a) shows a comparison of the incremental heading obtained from on-board position estimates (SPICE) with that obtained from the independently measured position of the rover (GTS), only for those time values when the independent measurements are available. Also shown are the mean sun sensor heading, and the desired heading to the waypoint.

Since the incremental heading estimate is essentially a derivative of the position, it is an extremely noisy signal. If used instead of a the sun sensor to estimate heading, the propagated estimate of rover position appears as the random walk shown in Figure 11(b). This is in strong contrast to the position estimate propagated with the measured heading obtained from the sun sensor, as shown by the solid line in the same plot.

5.3.2 Angular Rate Sensor

When used in conjunction with odometry, angular rate sensing provides much better performance than odometry alone, but still significantly poorer than sun sensing. This can best be seen by developing a sensor model similar to that provided in Section 5.2.1. In the case of the rate sensor, the noise is in the rate signal:

$$\theta = \int_0^t (\dot{\theta}_0 + n_\omega) d\tau \quad (7)$$

$$= \theta_0 t + n_\omega t \quad (8)$$

Again, for simplicity let $\theta_0 = 0$. Therefore, if the rover speed is v , its (x, y) position will be:

$$x = \int_0^t v \cos n_\omega \tau d\tau \quad y = \int_0^t v \sin n_\omega \tau d\tau \quad (9)$$

$$x = \frac{v}{n_\omega} \sin n_\omega t \quad y = \frac{v}{n_\omega} (1 - \cos n_\omega t) \quad (10)$$

	Units	Rocky 7	Sojourner	Rocky 3
Heading Sensor		sun	rate	rate
Total Odometry (d)	m	395	98	335
Average Traverse	m	132	2.1	8.4
Number of Traverses		3	46	38
Speed of Moves (v)	m/s	0.12	0.01	0.15
Relative Heading Error (n_ω/v)	mrاد/m	(0.4)	16	5
Rate of Heading Error (n_ω)	mrاد/s	—	0.16	0.75
Absolute Heading Error (n_θ)	mrاد	60	(105)	(83)
Relative Position Error (e/d)	%	6	—	—

Table 2: Comparison of traverse performance numbers for Rocky 7 using a sun sensor, and Sojourner and Rocky 3 which use an angular rate sensor.

Again, the straight traverse value of $x = vt = d$ is used to determine the position error:

$$e = \frac{v}{n_\omega} \sqrt{(n_\omega t - \sin n_\omega t)^2 + (1 - \cos n_\omega t)^2} \quad (11)$$

In the extremes of large and small values for time, this result may be approximated as:

$$t \rightarrow 0 : e \approx \frac{n_\omega}{v} \frac{d^2}{2} \quad (12)$$

$$t \rightarrow \infty : e \approx d \quad (13)$$

where the Taylor series expansion has been used for the first result. For small distances, the error grows as square of the distance traversed. For intermediate distances, the rate error causes the rover to drift in a circle, and its position error grows precipitously after $nt = \pi/2$. For large desired distances, the rover will essentially drive in a circle, not making any significant forward progress, and the error becomes equal to the traversal distance.

Despite these obvious problems, angular rate sensors have been used successfully for short traverses with the JPL microrovers Rocky 3, in the laboratory, and Sojourner, on Mars⁶. To better appreciate Rocky 7 desert test performance, it can be directly compared with data obtained previously in experiments with Rocky 3, and new data from Sojourner [9, 3].

Table 2 shows the results for traverses performed by all three rovers. Not only did Sojourner have very short average traverse lengths, but its commanded traversals varied greatly from one day of the mission to the next. In contrast, Rocky 3 was consistently commanded to go a fix distance in a laboratory setting. Both rovers drove in terrain that was mostly “Mars nominal” (i.e. terrain with a rock density average for the Martian surface) [11].

The relative heading error for Sojourner is much larger than Rocky 3, as expected by its slow speed. However, it is interesting to note that when vehicle speed is taken into consideration, the rate of heading error is much less for Sojourner. This improvement is

⁶Both used the same sensor: model QRS-11 from Systron Donner.

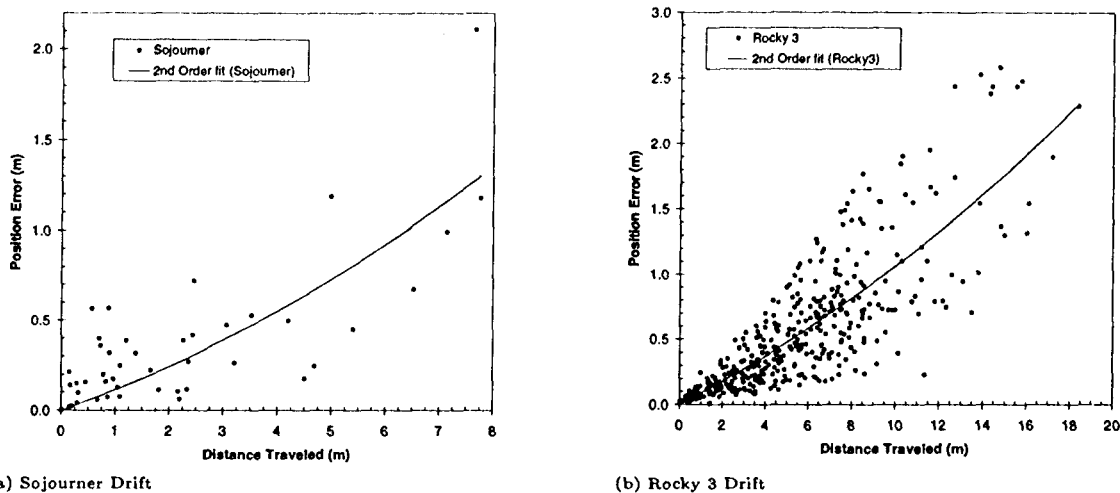


Figure 12: Position error data using angular rate sensor: (a) for Sojourner rover on Mars, and (b) for Rocky 3 test vehicle in laboratory.

either due to its flight approved electronics, or the reduced vibration noise of low speed travel.

The parameter values for heading error of Sojourner and Rocky 3 have been extracted from the position errors shown in Figures 12. The large variance in the data indicates the noisy quality of rate sensing. Both plots may be compared with Rocky 7's performance shown in Figure 8. Rocky 7 and 3 results include intermediate position errors, whereas only end of traverse error is provided for Sojourner.

To verify that Rocky 7 error is linear with distance, a quadratic fit was made to the data shown in Figure 8. The linearity of the data is confirmed by the small Relative Heading Error, provided in parenthesis in Table 2, which is an order of magnitude less than that for Rocky 3 and Sojourner. Without an obvious connection to vehicle speed, this term has not been normalized as a Rate of Heading Error. The use of a quadratic fit actually reduces the size of the Absolute Heading Error to 42 mrad.

Conversely, the quadratic fit to the Sojourner and Rocky 3 data has a substantial linear term, which is provided in Table 2 with parentheses, under Absolute Heading Error. The cause of this term is unknown, but is probably be due to slippage. Such an explanation is consistent with slippage being the cause of differences in the relative heading errors obtained for Rocky 7, shown above in Figures 7. This linear term for the rate sensor is alone as large as the sun sensor error. The addition of the the quadratic term makes it very clear that use of the angular rate sensor is unsuitable for long range traversing.

6 Improvements

Even with the improvements provided by sun sensing, plans for ten kilometer traverse missions across Mars indicate the need to provide even better position estimation. Such

information is valuable for scientific understanding of surface features, correlation of ground images with orbital or descent images, and precision-landing rendezvous with the rover for sample return.

Several efforts are underway to improve position estimation of the rover. First, improved calibration of the sun sensor will be accomplished along with the use of a more precise optics model. Second, terrain features and topology will be tracked at multiple resolutions to visually estimate changes in rover position and orientation. Third, improved odometry estimation will result from improved path planning that reduces the total distance traveled and restricts it to the best terrain for driving. Fourth, local terrain will be monitored with the attitude and rocker bogey sensors to compensate for topological effects. Finally, the results of all techniques will be statistically combined on-board the rover [7].

7 Summary

This paper has presented the results of development and testing of the next-generation rover prototype, Rocky 7. This rover has been created specifically to validate the mission concept of long range navigation across Mars. To this end the rover was given the ability to provide panoramic images to remote operators, from which navigation targets are selected and provided back to the rover. Key to Rocky 7's ability to successfully navigate to these sites, is precise on-board position estimation (6% relative error) based largely on sun sensing for heading measurement. Desert field trials of the rover have validated this operational technique and shown significant improvements over previous direction sensing schemes.

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In the large experimental systems discussed in this paper there are many individuals contributing. Ground truth data was collected by Curt Niebur and Judd Bowman of Washington University. Data processing within the SPICE system was performed by Boris Semenov. Rocky 7 telemetry data was captured by Steve Peters. All operations and path specification was performed Greg Tharp and Ray Arvidson. In addition, the rest of the Rocky 7 development and field test team include: Tim Ohm, J. (Bob) Balaram, Robert Ivlev, Samad Hayati, Paul Backes, Richard Petras, Sharon Laubach, and Alejandro Martin-Alvarez. Sojourner performance data was obtained by the Mars Pathfinder flight team, and compiled by Tam Nguyen. Rocky 3 test data was obtained by Reid Harrison and provided by Larry Matthies.

References

- [1] C. Acton. Ancillary Data Services of NASA's Navigation and Ancillary Information Facility. *Planetary and Space Science*, 44(1):65-70, 1996.
- [2] R. Arvidson et al. Rocky 7 Prototype Mars Rover Field Geology Experiments: 1. Lavic Lake and Sunshine Flow Volcanic Field, California. *Journal of Geophysical Research - Planets*, Submitted.
- [3] Wilcox B. and T. Nguyen. Sojourner on Mars and Lessons Learned for Future Planetary Rovers. In *Proceedings of the Society of Automotive Engineers, 28th International Conference on Environmental Systems (ICES)*, Danvers Massachusetts, July 13-16 1998.
- [4] P. Backes, K. Tso, and G. Tharp. Mars Pathfinder Mission Internet-Based Operation Using WITS. In *IEEE International Conference on Robotics and Automation*, Leuven, Belgium, May 1998.
- [5] D. Bickler. A New Family of JPL Planetary Surface Vehicles. In *Missions, Technologies, and Design of Planetary Mobile Vehicles*, pages 301-306, Toulouse, France, September 28-30 1992.
- [6] R. Brooks. A Robust Layered Control System for a Mobile Robot. *IEEE Journal on Robotics and Automation*, 2(1), March 1986.
- [7] H. F. Durrant-Whyte. Consistent Integration and Propagation of Disparate Sensor Observations. In *IEEE International Conference on Robotics and Automation*, pages 1464-1469, April 1986.
- [8] E. Gat et al. Behavior Control for Robotic Exploration of Planetary Surfaces. *IEEE Transactions on Robotics and Automation*, 10(4):490-503, 1994.
- [9] L. Matthies, E. Gat, R. Harrison, B. Wilcox, R. Volpe, and T. Litwin. Mars Microrover Navigation: Performance Evaluation and Enhancement. *Autonomous Robots Journal, Special Issue on Autonomous Vehicle for Planetary Exploration*, 2(4), 1995.
- [10] L. Matthies and P. Grandjean. Stochastic Performance Modeling and Evaluation of Obstacle Detectability with Imaging Range Sensors. *IEEE Transactions on Robotics and Automation*, 10(6):783-791, December 1994.
- [11] H. Moore and B. Jakosky. Viking landing sites, remote-sensing observations, and physical properties of Martian surface materials. *Icarus*, 81:164-184, 1989.
- [12] S. Price et al. Microrover Sensor Suite Design. Phase II Final Report 959855, Lockheed Martin Astronautics, Denver, CO, June 27 1996.
- [13] S. Schneider, V. Chen, and G. Pardo-Castellote. ControllShell: A Real-Time Software Framework. In *AIAA Conference on Intelligent Robots in Field, Factory, Service, and Space (CIRFFSS)*, Houston, Texas, March 20-24 1994.

- [14] R. Volpe. Sun Sensor Heading Estimation for Mars Rover Navigation. *JPL Internal Memorandum*, June 1998.
- [15] R. Volpe, J. Balaram, T. Ohm, and R. Ivlev. The Rocky 7 Mars Rover Prototype. In *IEEE/RSJ International Conference on Robots and Systems (IROS)*, Osaka, Japan, November 4-8 1996.
- [16] R. Volpe et al. A Prototype Manipulation System for Mars Rover Science Operations. In *IEEE/RSJ International Conference on Robots and Systems (IROS)*, Grenoble, France, September 7-11 1997.
- [17] R. Volpe et al. Rocky 7: A Next Generation Mars Rover Prototype. *Journal of Advanced Robotics*, 11(4):341-358, 1997.
- [18] R. Volpe et al. Mobile Robot Manipulators for Mars Science. *Space Technology Journal*, 17(3/4):219-229, 1998.
- [19] W. Whittaker, D. Bapna, M. Maimone, and E. Rollins. Atacama Desert Trek: A Planetary Analog Field Experiment. In *Proceedings of i-SAIRAS Conference*, Tokyo Japan, July 1997.